CP Violating Asymmetry in Stop Decay into Bottom and Chargino

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Abstract. In the MSSM with complex parameters, loop corrections to the decay of a stop into a bottom quark and a chargino can lead to a CP violating decay rate asymmetry. We calculate this asymmetry at full one-loop level and perform a detailed numerical study, analyzing the dependence on the parameters and complex phases involved. In addition, we take the Yukawa couplings of the top and bottom quark running. We account for the constraints on the parameters coming from several experimental limits. Asymmetries of several percent are obtained. We also comment on the feasibility of measuring this asymmetry at the LHC.

Keywords: SUSY, MSSM, CP Violation, Decay, Complex Parameters, Loop Corrections, LHC
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INTRODUCTION

Supersymmetric extensions of the SM can contain new sources of CP violation, which can lead to an explanation of the baryon asymmetry of the universe (BAU) via Electroweak Baryogenesis. If one chooses some of the MSSM parameters to be complex, processes can lead to CP violating asymmetries. But even if BAU cannot be explained, studies of CP violation and values of potentially complex parameters are important.

DECAY RATE ASYMMETRY δ^{CP}

We define the CP violating decay rate asymmetry of the decay $\tilde{t}_i \to b\tilde{\chi}_k^+$ as

$$\delta^{CP} = (\Gamma^+(\tilde{t}_i \to b\tilde{\chi}_k^+) - \Gamma^-(\tilde{t}_i^* \to \bar{b}\tilde{\chi}_k^{+c}))/(\Gamma^+(\tilde{t}_i \to b\tilde{\chi}_k^+) + \Gamma^-(\tilde{t}_i^* \to \bar{b}\tilde{\chi}_k^{+c}))\,. \tag{1}$$

We write the one-loop decay widths as $\Gamma^\pm \propto \sum_s |\mathcal{M}^\pm_{\rm tree}|^2 + 2{\rm Re}(\sum_s (\mathcal{M}^\pm_{\rm tree})^\dagger \mathcal{M}^\pm_{\rm loop})$. Since there is no CP violation at tree-level and assuming that the one-loop contribution is small compared to the tree-level, the decay rate asymmetry can be approximated by

$$\delta^{CP} \cong \frac{\Gamma^+ - \Gamma^-}{2\Gamma_{\rm tree}} = A_+^{CP} - A_-^{CP} \quad , \quad A_\pm^{CP} = {\rm Re}\Big(\sum_s (\mathcal{M}^\pm_{\rm tree})^\dagger \mathcal{M}^\pm_{\rm loop}\Big) / \sum_s |\mathcal{M}_{\rm tree}|^2\,. \tag{2}$$

The matrix elements $\mathcal{M}^\pm_{\rm tree}$ and $\mathcal{M}^\pm_{\rm loop}$ are functions of the couplings $B^{R,L}_\pm$ and form factors $\delta B^{R,L}_\pm$, respectively. The explicit forms are given in [1]. Introducing $C^{ij}_\pm = B^i_\mp \delta B^j_\pm$ $(i,j = R,L)$ we can express $\mathcal{M}^\pm_{\rm loop}$ in terms of ${\rm Re}(C^{ij}_\pm)$ which have the structure

$${\rm Re}(C^{ij}_\pm) \propto {\rm Re}((bg_0g_1g_2)^\pm \times {\rm PaVe}) = {\rm Re}(bg_0g_1g_2){\rm Re}({\rm PaVe}) \mp {\rm Im}(bg_0g_1g_2){\rm Im}({\rm PaVe})$$

where $(bg_0g_1g_2)^-$ means complex conjugate, b is the coupling at tree-level, $g_0g_1g_2$

are couplings of the three vertices and PaVe stands for the Passarino-Veltman-Integrals. This leads to the decomposition into both CP invariant and CP violating parts $\mathrm{Re}(C^{ij}_{\pm}) = C^{ij}_{\mathrm{inv}} \pm C^{ij}_{\mathrm{CP}}\ /\ 2$ with the definitions $C^{ij}_{\mathrm{inv}} \propto \mathrm{Re}(bg_0g_1g_2)\mathrm{Re}(\mathrm{PaVe})$ and $C^{ij}_{\mathrm{CP}} \propto -2\mathrm{Im}(bg_0g_1g_2)\mathrm{Im}(\mathrm{PaVe})$. We can see that we need not only the couplings but also the PaVe's to be complex (i.e. at least a second decay channel kinematically open) in order to obtain a non-zero δ^{CP}. The asymmetry $\delta^{CP} = A^{CP}_{+} - A^{CP}_{-}$ becomes

$$\delta^{CP} = \Big(\Delta(C^{RR}_{\mathrm{CP}} + C^{LL}_{\mathrm{CP}}) - 2m_b m_{\tilde{\chi}^+_k}(C^{RL}_{\mathrm{CP}} + C^{LR}_{\mathrm{CP}})\Big) / \sum_s |\mathcal{M}_{\mathrm{tree}}|^2\ ,\ \Delta = (m^2_{\tilde{t}_i} - m^2_b - m^2_{\tilde{\chi}^+_k})$$

where one can neglect the second term due to the smallness of the bottom mass.

CP VIOLATING CONTRIBUTIONS

In principle, 47 one-loop diagrams can contribute. If the channel $\tilde{t}_i \to t\,\tilde{g}$ is kinematically open, the selfenergy graph in Fig. 1 and the vertex graph with $\tilde{g}$ exchange should dominate due to the strong coupling. But numerically only the selfenergy graph dominates and we thus concentrate on this diagram.

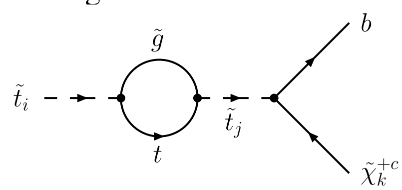

FIGURE 1. Leading contribution of CP violation in $\tilde{t}_i \to b\tilde{\chi}^+_k$ at one-loop level in the MSSM with complex couplings $(i, j, k = 1, 2)$.

The general matrix element can be written as $\mathcal{M}^+ = i\bar{u}(k_1)(\delta B^R_+ P_R + \delta B^L_+ P_L)v(-k_2)$. The couplings as well as the Passarino-Veltman-Integrals are defined in [1]. The form factor for the process is

$$\delta B^R_+ = 2m_{\tilde{g}} m_t B^R_{kj}(G^{R*}_i G^L_j + G^{L*}_i G^R_j)B_0/((4\pi)^2(m^2_{\tilde{t}_i} - m^2_{\tilde{t}_j})) \tag{3}$$

using the arguments $(m^2_{\tilde{t}_i}, m^2_{\tilde{g}}, m^2_t)$ for the B_0-function. Note that $i \neq j$ in order to contribute to CP violation.

NUMERICAL RESULTS

We present numerical results for the decay rate asymmetry δ^{CP} as well as the branching ratio (BR) of the process $\tilde{t}_1 \to b\tilde{\chi}^+_1$. The 47 contributions were calculated by using FEYNARTS [2]. Furthermore, the two gluino graphs and others we calculated independently and also cross checked numerically. Our parameter points are consistent with constraints coming from the EDM of the electron (private code), $B \to X_s\gamma$ and the cold dark matter relic density (MICROMEGAS [3]).
For the MSSM input parameters we take the 3rd generation SUSY breaking parameters $M_{\tilde{Q}} = M_{\tilde{u}} = M_{\tilde{d}} = 650$ GeV and $M_{\tilde{L}} = M_{\tilde{e}} = 600$ GeV, $|A_t| = |A_b| = |A_\tau| = 190$ GeV and the complex phases $\varphi_{A_t} = \varphi_{A_b} = \varphi_{A_\tau} = \pi/4$, $\varphi_\mu = 0$, $\varphi_{M_1} = 0$ and $\varphi_{\tilde{g}} = 0$ (at first). We further set $M_2 = 150$ GeV, $|M_1| = M_2/2$, $|\mu| = 830$ GeV, $\tan\beta = 5$, and $M_{A^0} = 1000$ GeV.

These parameters imply that φ_{A_t} is at first the only source of CP violation, the chargino $\tilde{\chi}_1^+$ is gaugino-like, and $\tilde{t}_1$ and $\tilde{t}_2$ have a low mass splitting but high mixing.
In Fig. 2 we show δ^{CP} and BR as a function of $m_{\tilde{t}_1}$ for $\tan\beta = 5, 10, 15$. The parameter $m_{\tilde{t}_1}$ is shown for convenience, the parameter actually varied is $M_{\tilde{Q}}$ from 500 to 1000 GeV. One can see the threshold of the $\tilde{t}_1 \to \tilde{g}t$ decay at ~ 583 GeV, after which the gluino contributions account up to $\sim 98\,\%$ to δ^{CP}. However, if this decay channel opens, the BR drops quickly. This general feature and thus permanent conflict between δ^{CP} and

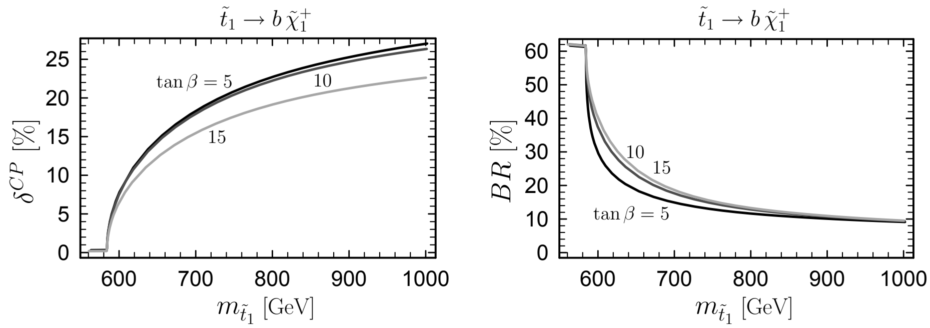

FIGURE 2. δ^{CP} and BR as a function of $m_{\tilde{t}_1}$ ($M_{\tilde{Q}}$ varied) for various values of $\tan\beta$.

$BR(\tilde{t}_1 \to b\tilde{\chi}_1^+)$ can also be seen in Fig. 3a. If $\tilde{t}_1 \to \tilde{g}t$ is possible, δ^{CP} is large but BR is small. Below the threshold of $\tilde{t}_1 \to \tilde{g}t$, δ^{CP} remains small and BR is large. The solution for an optimal measurable effect is to compromise.
In Fig. 3b we show the dependence on the gluino phase $\varphi_{\tilde{g}}$ as a second source of CP violation. One can see the periodic behaviour of $\varphi_{\tilde{g}}$ and the dependence on φ_{A_t}. The BR shows also a strong dependence, with higher values for higher φ_{A_t} and $\varphi_{\tilde{g}} \in [\pi/2, \pi]$.

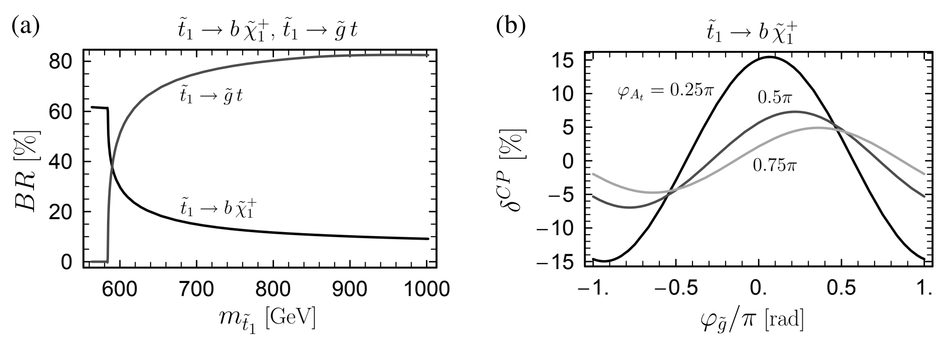

FIGURE 3. (a) Comparison of $BR(\tilde{t}_1 \to b\tilde{\chi}_1^+)$ and $BR(\tilde{t}_1 \to \tilde{g}t)$ as a function of $m_{\tilde{t}_1}$ ($M_{\tilde{Q}}$ varied). (b) δ^{CP} as a function of $\varphi_{\tilde{g}}$ for various φ_{A_t}.

The reason for the strong suppression of the gluino vertex graph lies in its complicated form factor, and we have not found a simple explanation yet.
The effect on the mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$ is shown in Fig. 4. We fix $m_{\tilde{t}_1} = 650$ GeV and vary $m_{\tilde{t}_2}$ by changing the parameters $M_{\tilde{Q}}, M_{\tilde{U}}$. The two solutions for $M_{\tilde{Q},\tilde{U}}(m_{\tilde{t}_2})$ are $m_{LL} \lessgtr m_{RR}$. The combination of δ_{CP} and BR keeps low in both solutions, unless the mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$ is small (due to enhancement of the $\tilde{t}_2$ propagator $\propto 1/(m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)$ in the gluino selfenergy graph).

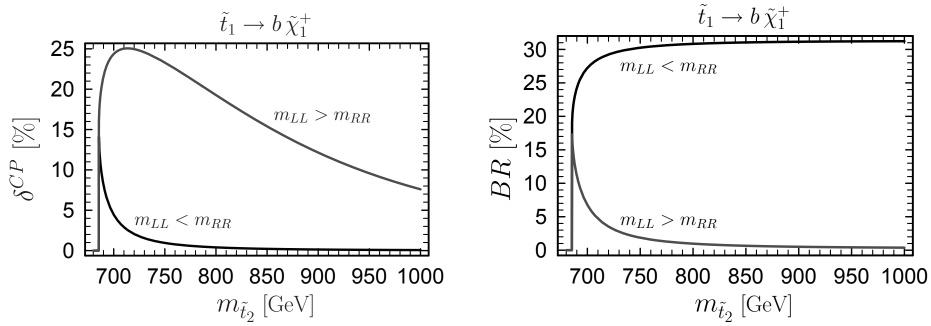

FIGURE 4. Effect on mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$ showing δ^{CP} and BR as a function of $m_{\tilde{t}_2}$ ($M_{\tilde{Q}}, M_{\tilde{U}}$ varied, both solutions) for $m_{\tilde{t}_1} = 650$ GeV.

We have calculated the total cross section for $\tilde{t}_1$ pair production at the LHC with PROSPINO [4]. For $\sqrt{s} = 14$ TeV, $m_{\tilde{t}_1} = 610$ GeV and $m_{\tilde{t}_2} = 710$ GeV we obtain $\sigma = 200$ fb at NLO. Assuming $\mathcal{L} = 300\,\mathrm{fb}^{-1}$ (5 years), we estimate the number of CP violating events to $N = \mathcal{L} \times \sigma \times \delta^{CP} \times BR = 1200$ with $\delta^{CP} = 0.1$ and $BR = 0.2$. A possible signature is the subsequent decay $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W^{\pm} \to \tilde{\chi}_1^0 l \nu_l$. Understanding the MSSM particle properties well enough, δ^{CP} can be measured at the LHC.

CONCLUSIONS

In the MSSM with complex parameters, loop corrections to the $\tilde{t}_i \to b\widetilde{\chi}_k^+$ decay can lead to a CP violating decay rate asymmetry δ^{CP}. We studied this asymmetry at full one-loop level, analyzing the dependence on the parameters and phases. A δ^{CP} of several percent is possible, mainly due to the gluino contribution in the selfenergy loop. The asymmetry can be large for low mass splitting and high mixing of the stop particles, and the chargino needs a strong wino component. But δ^{CP} must be always seen in relation to BR and σ_{prod}. The measurement should be possible already at the LHC.

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REFERENCES

1. S. Frank, *CP Violating Asymmetries Induced by Supersymmetry*, Master's thesis, Johannes Kepler University Linz (2008), arXiv:0909.3969.
2. T. Hahn, *Comput. Phys. Commun.* **140**, 418–431 (2001), hep-ph/0012260.
3. G. Belanger, F. Boudjema, S. Kraml, A. Pukhov, and A. Semenov, *Phys. Rev.* **D73**, 115007 (2006), hep-ph/0604150.
4. W. Beenakker, M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, *Nucl. Phys.* **B515**, 3–14 (1998), hep-ph/9710451.